A

DISSERTATION ON

ADAPTIVE DISTANCE RELAY SETTING FOR PARALLEL TRANSMISSION NETWORK CONNECTING WIND FARMS AND UPFC

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CANDIDATE'S DECLARATION

I hereby certify that this report which is being presented in the seminar entitled **"ADAPTIVE DISTANCE RELAY SETTING FOR PARALLEL TRANSMISSION NETWORK CONNECTING WIND FARMS AND UPFC"** in partial fulfilment of the requirement of award of Degree of **Master of Technology** in **Electrical Engineering with specialization in** ***Power Systems Engineering***, submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee , India is an authentic record of the work carried out during a period from May 2015 to May 2016 under the supervision of **Dr. C.P.Gupta**, Department of Electrical Engineering, Indian Institute of Technology, Roorkee. The matter presented in this dissertation has not been submitted by me for the award of any other degree of this institute or any other institute.

Date :

Place : Roorkee **(KAMAL JOSHI)**

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to best of my knowledge.

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I would like to dedicate this thesis to my beloved parents and to my brothers and sister for their love and support to me.

(KAMAL JOSHI)

ABSTRACT

An adaptive distance relay setting for parallel transmission lines when a unified power flow controller and wind farm are connected to a parallel transmission network. An ideal trip characteristic of distance relay is significantly affected as the apparent impedance seen by the relay is affected. Reach setting of distance relay is affected when a wind farm is connected to it because of continuous fluctuation in relay voltage. Transmission-Line protection in the presence of a unified power-flow controller (UPFC) is one of the major challenging issues in power system protection. The presence of the UPFC in a fault loop affects the steady state and transient component in the voltage and current signals.

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Chapter 1 Introduction

1.1 Overview

Location of fault is amongst the most imperative issues in transmission system. A fault event might cause electricity break down in some zones. By Knowing exact fault distance will helps the administrators to find it speedier and re-establish the line back quicker. The standard two-terminal fault location is an exact technique to find the fault point on transmission line by measured information from both terminals. Be that as it may, now a days double line circuits are utilized as a part of numerous nations transmission systems. On account of double line circuit, the line is altogether influenced by measured impedance and shunt capacitance. So relay exhibitions influenced because of this during fault. During fault positive sequence segment and negative sequence components are cancels out so there impact is unimportant however zero sequence component it is additive in nature, it influences relay performances. So adaptive distance relay is required to make system more solid and secure during fault.

Presence of unified power flow controller (UPFC) in a transmission system makes the protection of transmission system in a power system is exceptionally testing issue now a days as it influences the impedance seen by the relay. At the point when UPFC is available in the faulted section, it influences the steady state and transient part in the voltage and current signals at relay point. In this way, the voltage and current signals observed at the relay point and will be modified by influencing the performance of the current protection scheme.

Now a days, wind farms are coordinated to the matrices at various voltage levels over the world. Power shared by wind farms are expanding day by day. Due to uncontrollable speed of wind, its integration to the grid causes problem. The fluctuation in voltages and frequency due to uncontrollable speed are solved to a extent by using power electronics based control arrangement in wind farm. “The variation in wind speed also results in fluctuating output power. The output power of a wind farm unit has a nonlinear relationship with the wind speed” [3]. Wind farms connected to grid only contributes power to the grid when wind speed is within specified limits. And when the speed is beyond the limits, the farm cannot contribute to the grid. So the distance relaying protection scheme is also affected due to fluctuating power throughout a day.

The ideal trip attributes of distance relay characteristics will be one that deals with arc segment resistance all through length of a line and ought to involves least region in the R-X diagram. Area in R-X plane should be as small as possible to make it slightest influenced by power swing. Assuming the arc resistance is steady all through the line length. The ideal characteristics in R-X plane will be a Quadrilateral as appeared in Fig 1.1. Now we are living in digital era so by using digital any relay can be designed for any characteristics unlike conventional relays i.e. mho relay characteristics. Henceforth, Now a days quadrilateral characteristics is being used as an ideal distance relay characteristic.

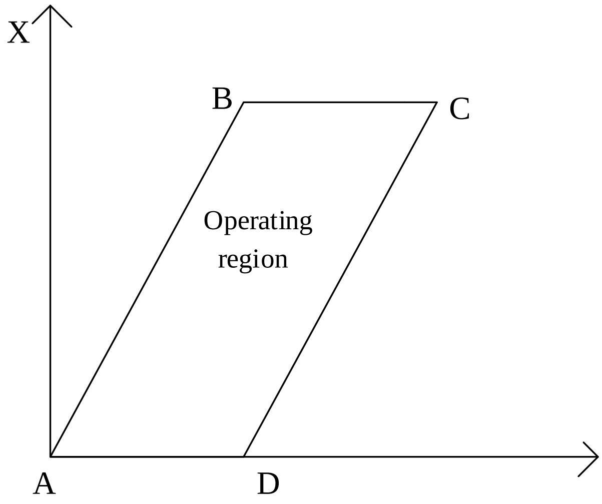

Fig 1.1 Quadrilateral characteristics of distance relay

As we know Distance relay has additional feature of back up protection which makes it very important and extensively used for protection of long tine transmission system. The digital version of the distance relay gives better observing, communication and adaption to the system conditions. In a constant setting approach, system is studied once and on the basis of overall study, system characteristics are defined. Limit of relay setting is predefined in view of general system study. While consolidating adaptive element in this distance relay is set online in as per winning system conditions. Due to adaptive feature of the distance relay reliability of protection system ultimately increase.

Now a days, pattern is to utilize quadrilateral attributes based distance relay protection for all kind of line shortcomings to arrange with high fault resistance if there should be an occurrence of ground fault. They give higher resistive achieve when contrasted with a standard mho circle having same greatest affectability point and forward reach. The scheme is versatile to change in conditions like change in source impedance and system impedance, loading level, voltage magnitude ratio and frequency etc.

1.2 Quadrilateral characteristics

Quadrilateral characteristics is appeared in Fig1.1 forward span and resistive reach settings can be balanced freely. Along these lines it gives better result on account of high fault resistance than any mho relay sort trademark for short transmission lines. On account of earth fault impedance estimation, it is noteworthy the value of fault resistance includes the arc resistance and fault resistance to earth. Normally maximum resistance of fault is taken into consideration for zone reach setting so that error can be reduced. If system conditions are fixed and fault resistance RF and fault location from the relay point P varied accordingly, four limit lines are acquired by matlab programming.

Case A: Faults at a relay-reach end that is at 80% of line length that means p is fixed at 0.8 and fault resistance varied from 1 Ω to 200 Ω in a step of 20 Ω.

Case B: Faults at different points that is p is varied from 0.01 to 0.8 with a constant 200 Ω fault resistance.

Case C: Faults at the relaying point that means p=0.01 fixed and fault resistance varied from 1 Ω to 200 Ω in a step of 20Ω.

Case D: Solid Faults at different points that is p is varied from 0.01 to 0.8 with a constant 1Ω fault resistance.

The four lines drawn in Fig 1.2 frames the quadrilateral attributes and the included area in Fig 1.2 shapes a perfect outing area under the predominant system conditions. Be that as it may, the system arrangement and its working conditions influence the deliberate reactance and resistance at relay location; i.e. these four lines and the included region will change as system conditions and setup changes as per system conditions.

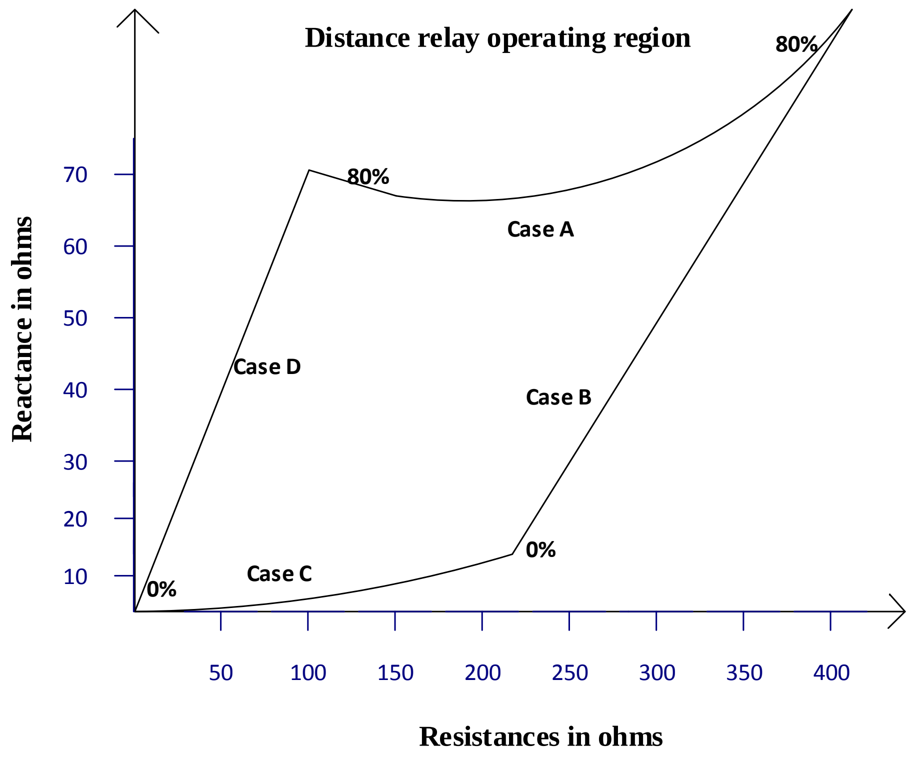

Fig 1.2.Triping boundary of distance relay

Chapter 2 Literature Review

2.1 Research Motivation

To implement the adaptive distance relay setting of distance relay for parallel system interfacing farms and unified power flow controller together. In the proposed study the setting of adaptive relay of transmission line is developed and the impact of wind farm and UPFC on the same are considered. "The proposed study approach ascertains the real impedance seen by relay to the fault point incorporating varieties in system parameters in UPFC. For example, level of compensation, power transfer angle, fault resistance and fault location and variety in infiltration level of wind farm at various loading levels, voltage magnitude and source impedance and mutual inductance and in addition shunt capacitance are additionally included". In current study concentrated just on single line to ground fault is considered and it can be stretched out to different faults too.

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2.2 Research Background

Now a days for higher voltage level and long distance transmission parallel network transmission system is used to carry power from one place to another. But in parallel network transmission mutual coupling and shunt capacitances affects the impedance of transmission line. "Reach accuracy of a distance relay is adversely affected by pre fault system conditions, ground fault resistance, shunt capacitance, and mutual coupling of parallel lines"[1].

To increase the power transfer capability of a line FACTs devices such as UPFC are used for long transmission line. UPFC impedance changes dynamically when it is used in power system. So it affects distance relay setting of the transmission line and opens wide challenges in the area of adaptive relay setting. "P. K. Dash *et al.* [2] presented the apparent impedance calculations and the distance relay setting characteristics for faults involving the UPFC and the ones that exclude the UPFC. The presence of an important flexible AC transmission systems FACTS device like unified power flow controller (UPFC) can drastically affect the performance of a distance relay in a two-terminal system connected by a double-circuit transmission line" [2].

And now a days wind energy is injected a lot in the power system and as wind farm only contribute to the system when wind speed is within the specified range. "A.K. Pradhan et al.[3] presented the apparent impedance seen by relay as the wind speed varies continuously throughout a day resulting in fluctuating wind farm output power, when such a farm is connected to the grid through a transmission line, the transmitted power to the grid and the relay end voltage (with respect to grid voltage) fluctuate continuously, the protection of such a line with distance relay is investigated. The ideal trip characteristic for distance relay is studied with change in conditions of the wind farm" [3].

2.3 Objective of the Thesis

In the proposed study, the adaptive relay setting of the parallel system is created here. What's more, same is reached out to the effect of wind farms and UPFC. The proposed study figures the right impedance seen by the relay when fault point incorporates the variety in parameters, for example, for various wind infiltration level and diverse loading level, source impedance, frequency and voltage extent and level of compensation of UPFC, fault resistance and fault location and so forth.

The main objectives of thesis are to:

1. System Studied and computation of apparent impedance including mutual coupling and shunt admittance.
2. Apparent impedance estimation for system in presence of UPFC.
3. Derivation of Apparent Impedance for Fault before UPFC.
4. Derivation of Apparent Impedance formula calculation for Fault after UPFC.
5. Generating quadrilateral limits for various condition utilizing MATLAB coding
    a. Variation in Wind farms parameters excluding UPFC
    b. Variation in UPFC parameters excluding wind farms
    c. Combined impact of Wind farms and UPFC both included

Chapter 3 Parallel Transmission System Considering Mutual Impedance

3.1 Analysis of distance relay in two terminal parallel transmission line

In conventional distance relay works in a view of apparent impedance observed by the relay at measuring point. When fault resistance is not present and during fault in first zone, impedance seen by a distance relay is same as the actual impedance between relaying point and faulted point has straight line relation with distance between the fault point to relay measuring point. But when fault resistance is present, the impedance seen by the relay at relaying point is not exactly equal to the above mentioned value of the transmission line. In this case, the impedance seen by the relay at relay location point relies on upon various operational conditions preceding the fault, mutual coupling between the parallel lines, shunt capacitance of line, load angle, fault condition and bus configuration etc. the measured impedance observed by the conventional distance relay during phase to earth fault is propositional to distance between fault point to relay location. Here only phase A to ground fault is considered but adaptive relay setting can be obtained for each and every fault.

The apparent impedance seen by relay at relaying point R with zero fault impedance is

$$Z_{aR}^{post} = \frac{V_{aR}^{post}}{I_{aR}^{post} + K_{0L} I_{0BA}^{post}} \tag{3.1}$$

Where, $$K_{0L} = \frac{Z_{0L1} - Z_{1L1}}{Z_{1L1}}$$

where, $V_{aR}^{post}, I_{aR}^{post}$ are the post-fault voltages and current at relay point R,

I_{0BA}^{post} is the post fault zero-sequence current at the relay point,

K_{0L} is the line zero sequence compensation factor,

p is the per-unit distance between relay and fault point,

Z_{0L1}, Z_{1L1} are the zero sequence and positive sequence impedances of Line1.

In this, for the examination of system showed up in Fig 3.1 is considered. The computerized distance relay at point 'R' is situated at bus in a transmission line 'TL1' which is effected by phase A-to-ground fault at point 'F' with a fault resistance of R_F, E_{am} and E_{an} are the comparable possibility at the two terminals. Voltage amplitude ratio of two terminal sources is h and δ is the power transfer angle or phase difference between two sources. Z_{sm}, Z_{sn} are the equivalent source impedances and Z_{L1}, Z_{L2} are the impedances of the transmission line TL1 and TL2 of the double line network system.

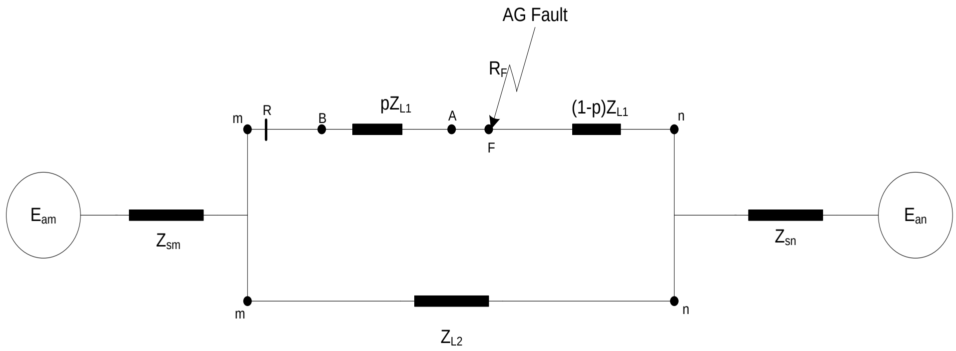

Fig 3.1 Parallel transmission network model

3.2 Analytical modeling of distance relay including the effect of mutual impedance

Investigation and Modeling of Fault Impedance Za amid SLG (single line to ground fault) Fault in transmission Line TL1 by considering mutual impedance:

The connection between apparent impedance observed by relay at Relay location and real present impedance from transport "M" to fault point "F" is determined in this segment.

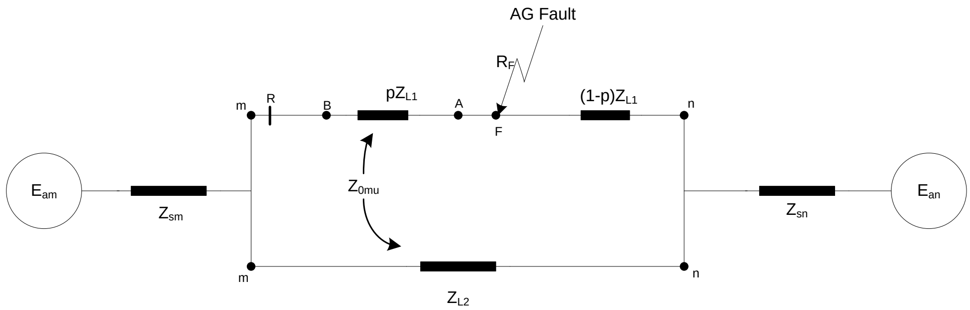

Fig 3.2 Showing fault in one of the transmission line

3.3 Calculation of Pre-Fault V_{preF} and I_{preF} using superposition theorem

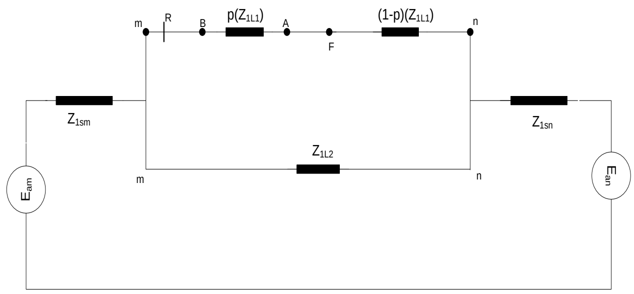

Fig 3.3 showing fault at a distance p from bus m

With Voltage source E_{am}

The pre-fault current in Z_{sm1} with only one source E_{am} is considered then

$$I_{z1sm}^{pre\_m} = \frac{E_{an}}{Z_{1sm}+Z_{1sn}+(Z_{1L1}||Z_{1L2})} \quad (3.2)$$

From Fig. 5, the pre-fault current in line TL1 when only one source E_{am} alone is considered:

$$I_{BF}^{pre\_m} = I_{z1sm}^{pre\_m}\left(\frac{Z_{1L2}}{Z_{1L1}+Z_{1L2}}\right) \quad (3.3)$$

$$I_{RB}^{pre\_m} = I_{BF}^{pre\_m} \quad (3.4)$$

With Voltage source E_{an}

Then, the pre-fault current in Z_{1sn}, Z_{1sm} when second source E_{an} is considered,

$$I_{z1sn}^{pre\_n} = \frac{E_{an}}{Z_{1sm}+Z_{1sn}+(Z_{1L1}||Z_{1L2})} \quad (3.5)$$

$$I_{z1sm}^{pre\_n} = I_{z1sn}^{pre\_n} \quad (3.6)$$

From Fig. 5.3, the pre-fault current in line TL1 when only second side source is considered,

$$I_{BF}^{pre\_m} = -I_{z1sn}^{pre\_n}\left(\frac{Z_{1L2}}{Z_{1L1}+Z_{1L2}}\right) \quad (3.7)$$

$$I_{RB}^{pre\_n} = I_{BF}^{pre\_n} \quad (3.8)$$

The pre-fault (Superposition) currents through Z_{1sm}, BF are given by:

$$I_{z1sm}^{pre} = I_{z1sm}^{pre\_m} - I_{z1sm}^{pre\_n} = \frac{E_{am}(1-he^{-j\delta})}{Z_{1sm}+Z_{1sn}+(Z_{1L1}||Z_{1L2})} \quad (3.9)$$

$$I_{BF}^{pre} = I_{BF}^{pre\_m} + I_{BF}^{pre\_n} \quad (3.10)$$

The pre-fault load current in phase-A in line L1 from R-to-B is given by,

$$I_{RB}^{pre} = I_{RB}^{pre\_m} + I_{RB}^{pre\_n} = \frac{E_{am}(1-he^{-j\delta})}{Z_{1sm}+Z_{1sn}+(Z_{1L1}||Z_{1L2})}\left(\frac{Z_{1L2}}{Z_{1L1}+Z_{1L2}}\right) = I_{preF} \quad (3.11)$$

The Superposition voltage at fault point 'F' is given by:

$$V_{preF} = E_{am} - Z_{1sm}\ I_{z1sm}^{pre} + pZ_{1L1}\ I_{BF}^{pre} \quad (3.12)$$

3.4 Calculation of Post-Fault I_{1F}, I_{2F}, I_{0F} and Z_{all}

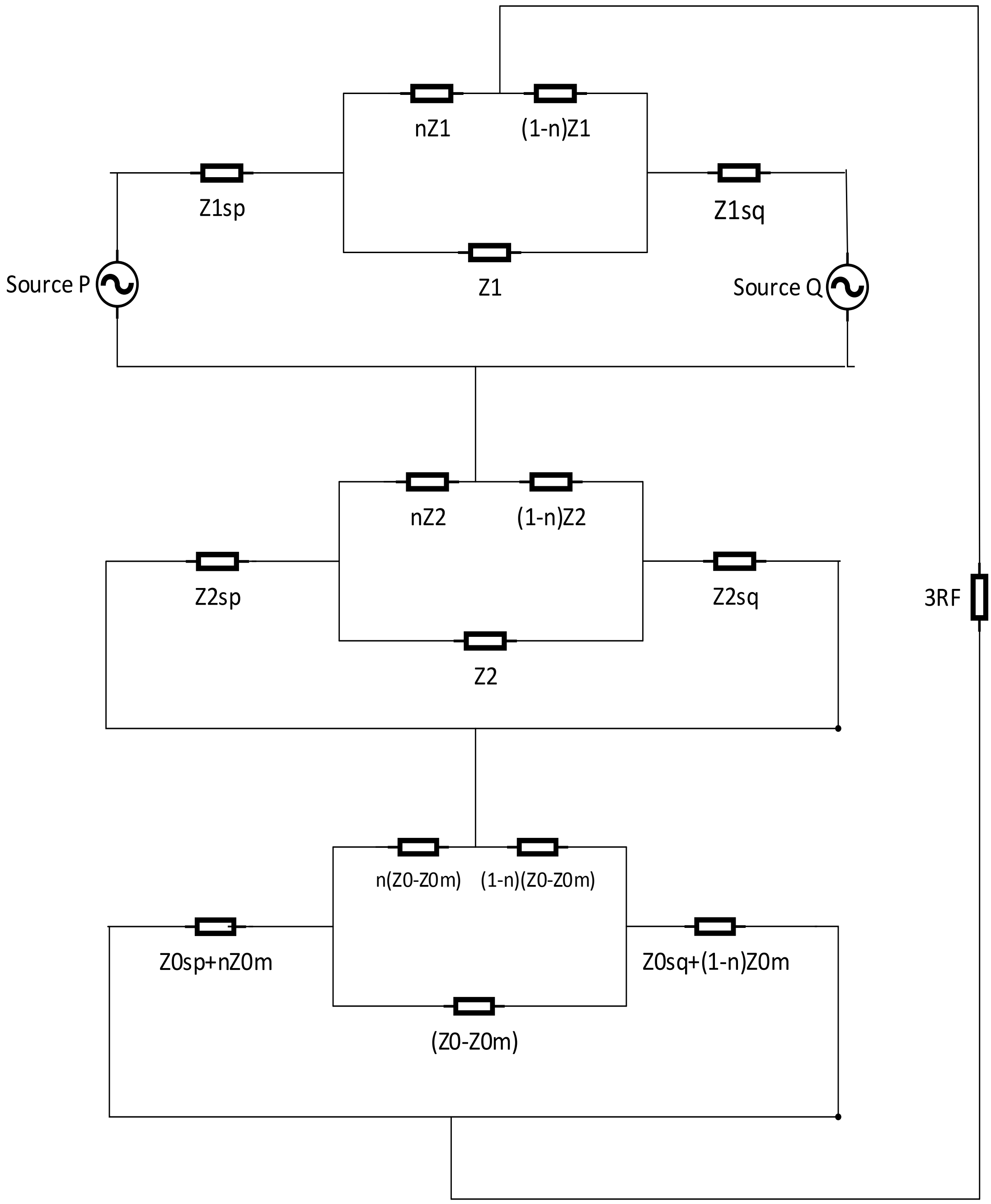

Fig 3.4 line to ground fault sequence diagram

Now delta to star transformation at the nodes M,N and F.

Let $Z_{1m}=Z_{1sm}+\frac{pZ_{1L1}Z_{1L2}}{Z_{1L1}+Z_{1L2}}$, $Z_{1n}=Z_{1sn}+\frac{(1-p)Z_{1L1}Z_{1L2}}{Z_{1L1}+Z_{1L2}}$,

$$Z_{mn}=\frac{p(1-p)Z_{1L1}Z_{1L1}}{Z_{1L1}+Z_{1L2}} \tag{3.13}$$

Then, $$Z_{+veseq} = \frac{Z_{1m}Z_{1n}}{Z_{1m}+Z_{1n}} + Z_{1mn} \quad (3.14)$$

$$Z_{-veseq} = Z_{+veseq} \quad (3.15)$$

Let $$Z_{0m} = Z_{0sm} + pZ_{0mu} + \frac{p(Z_{0L1}-Z_{0mu})(Z_{0L2}-Z_{0mu})}{(Z_{0L1}-Z_{0mu})+(Z_{0L2}-Z_{0mu})}$$

$$Z_{0n} = Z_{0sn} + (1-p)Z_{0mu} + \frac{(1-p)(Z_{0L1}-Z_{0mu})(Z_{0L2}-Z_{0mu})}{(Z_{0L1}-Z_{0mu})+(Z_{0L2}-Z_{0mu})}$$

$$Z_{0mn} = \frac{p(Z_{0L1}-Z_{0mu})+(1-p)(Z_{0L2}-Z_{0mu})}{(Z_{0L1}-Z_{0mu})+(Z_{0L2}-Z_{0mu})}$$

Then, $$Z_{0seq} = \frac{Z_{0m}Z_{0n}}{Z_{0m}+Z_{0n}} + Z_{0mn} \quad (3.16)$$

The +ve, -ve, zero sequence currents flowing through fault resistance R_F during the single line to ground fault in transmission line TL1 is given by,

$$I_{1F}^{post} = I_{2F}^{post} = I_{0F}^{post} = \frac{V_{preF}}{Z_{\Sigma}+3R_F} \quad (3.17)$$

Where, $Z_{\Sigma} = Z_{+veseq} + Z_{-veseq} + Z_{0seq}$

3.5 Calculation of Post-Fault $I_{1RB}^{post}, I_{2RB}^{post}, I_{0RB}^{post}, V_{aR}^{post}$

$$V_{aR}^{post} = (I_{1F}^{post} + I_{2F}^{post} + I_{0F}^{post})\, R_F + \left(I_{RB}^{pre} + I_{1RB}^{post} + I_{2RB}^{post}\right)pZ_{1L1} + \left(I_{0RB}^{post}pZ_{0L1}\right) + (I_{0L2}^{post}pZ_{0mu}) \quad (3.18)$$

The +ve,-ve and zero sequence fault currents after fault at F, form M to F are given by:

$$I_{1BA}^{post} = I_{2BA}^{post} = \frac{V_{preF}}{Z_{\Sigma}+3R_F}\left(\frac{Z_{1L2}}{Z_{1L1}+Z_{1L2}}\right) \quad (3.19)$$

$$I_{0BA}^{post} = \frac{V_{preF}}{Z_{\Sigma}+3R_F}\left(\frac{Z_{0n}}{Z_{0m}+Z_{0n}}\right) \quad (3.20)$$

And it can also represented as

$$I_{0RB}^{post} = I_{0BA}^{post}, I_{1RB}^{post} = I_{1BA}^{post}, I_{2RB}^{post} = I_{2BA}^{post} \quad (3.21)$$

Therefore, current I_{aR}^{post} at relaying location 'R' is given by:

$$I_{aR}^{post} = I_{RB}^{pre} + I_{1RB}^{post} + I_{2RB}^{post} + I_{0RB}^{post} \quad (3.22)$$

Therefore, voltage of phase –a at relay location is given by:

$$V_{aR}^{post} = (I_{1F}^{post} + I_{2F}^{post} + I_{0F}^{post})\, R_F + \left(I_{BF}^{pre} + I_{1BA}^{post} + I_{2BA}^{post}\right)pZ_{1L1} + \left(I_{0BA}^{post}pZ_{0L1}\right) + (I_{0L2}^{post}pZ_{0mu}) \quad (3.23)$$

The zero sequence current in transmission line 'TL2' from 'M' to 'N' is given in terms I_{0BA}^{post} of is given by:

$$I_{0L2}^{post} = I_{0BA}^{post}\left(\frac{p(Z_{0sn})-(1-p)Z_{0sm}}{(1-p)(Z_{0sm}+Z_{0mu}+Z_{0L2})+(2-p)Z_{0sn}}\right) \tag{3.24}$$

3.6 Calculation of apparent impedance Z_{aR}^{post} at relay location 'R'

The impedance seen by relay (Z_a) at relay point R is given by

$$Z_{aR}^{post} = \frac{V_{aR}^{post}}{I_{aR}^{post}+K_{0L}I_{0BA}^{post}+K_{0m}I_{z0L2}^{post}} \tag{3.25}$$

Where, $K_{0L} = \frac{Z_{0L1}-Z_{1L1}}{Z_{1L1}}$ and $K_{0m} = \frac{Z_{0mu}}{Z_{1L1}}$

Then, $$Z_{aR}^{post} = \frac{V_{aR}^{post}}{I_{aR}^{post}+I_{0BA}^{post}\left(K_{0L}+K_{0m}\frac{I_{z0L2}^{post}}{I_{0BA}^{post}}\right)} \tag{3.26}$$

$$Z_{aR}^{post} = \frac{V_{aR}^{post}}{I_{aR}^{post}+I_{0BA}^{post}K'_{0L}}$$

$$Z_{aR}^{post} = f(Z_{1sm}, Z_{1sn}, Z_{0sm}, Z_{0sn}, Z_{1L1}, Z_{1L2}, Z_{0L1}, Z_{0L2}, Z_{0mu}, K_{0L}, K_{0m}, h, \delta, p, R_F)$$

Where f is a nonlinear function as far as prefault and postfault parameters: 0,1and 2 are the positive, negative, zero sequence values individually. During solid grounded fault with RF = 0, the condition (3.26) gets to be same as condition (3.1) which is the positive sequence impedance multiplied by proportion of line length up to fault point that is (p) of fault line under all conceivable system working conditions.

However, in the event of non-zero grounded fault condition, the evident impedance observed by the relay at relay locating point R not just relies on upon the positive sequence impedance of the faulted transmission line, additionally relies on upon system working conditions prior and afterward the fault and mutual impedance also affects. The deliberate impedance seen by the relay may over range or under range, and relies on upon mutual impedance whose extremity is chosen by the direction of current in both the transmission line TL1 and TL2. Relay may over reach if there should arise an occurrence of same course of current and under reach in the event of inverse flow of current in parallel lines. This above over reach and under reach brought on by the mutual coupling impact can be remunerated by selecting the most ideal limit states of the relay settings. Generally the diverse sorts of regular working methods of parallel lines during single stage to ground flaw on one line are

(i) both lines are in working mode
(ii) one-line exchanged off and grounded at both the ends.

A parallel line, as a rule is operated under the case (i) working condition. In this work, the demonstrating and examination is completed for the case (i) in which, both the lines are in operation mode when one of the line is influenced by single line to ground fault SLG . Under this condition, the impedance seen by the relay is ascertained for different estimations of system working conditions. It exhibits that the apparent impedance for different estimations of fault resistance from 0-200 ohms in a steps of 20 ohm for the particular estimations of fault location is varies by p from 0-0.8 of the line length.

Chapter-4 Effect of UPFC

In recent years, the use of power electronics devices are increasing day by day in transmission systems. Unified power flow controller is the most adaptive device. FACTS devices are utilized as part of the power system to improve the power system capability and controllability. The power transferred in a interconnected grid is constrained by stability and security limit. In any case, implementation of FACTS devices in power system opens new difficulties to insurance of transmission line as these devices changes evident impedance of ensured zone progressively. For performance of protection system must be analysed by taking into consideration of presence of FACTS devices in the power system. UPFC is the most versatile device of FACTS family and UPFC is a combination of series and shunt FACTS device [2]. STATCOM and SSSC are used to design the UPFC.

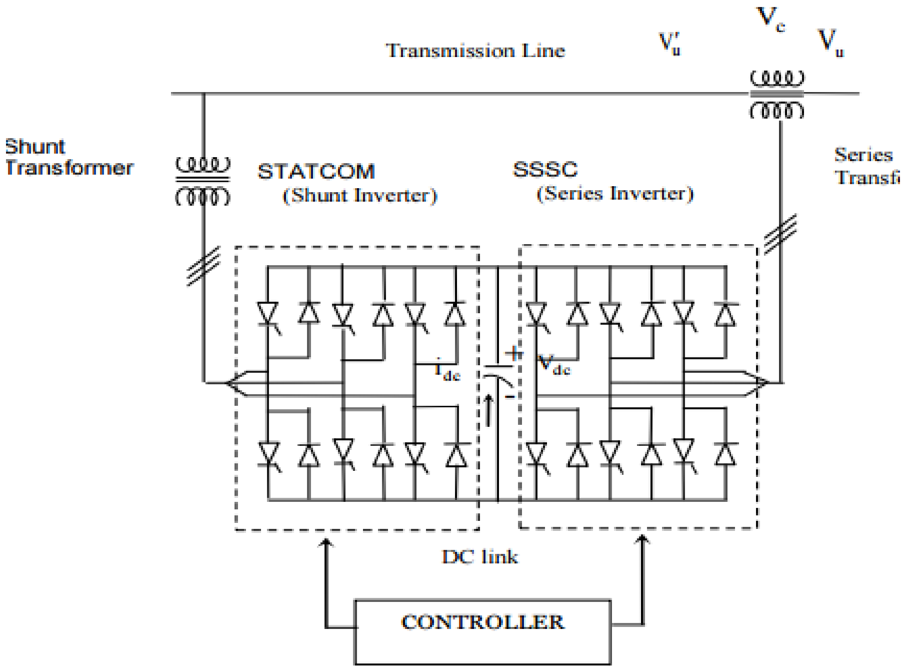

Fig 4.1 circuit diagram of UPFC

It has capability to control each and every parameters, voltage, phase angle and impedance which influences the power flow in a transmission lines. Arrangement pay expands the power exchange ability and enhances the transient stability of the system and damps out the motions oscillations. Assurance of power system with arrangement remuneration is viewed as most troublesome task. However line protection in light of distance relay additionally gets influenced by shunt FACTS devices. Protection of transmission line is based on distance relaying and impedance seen by the relay changes as the parameters changes.

Impedance seen by distance relay relies on upon the location of the fault as for UPFC location, evident impedance varies in both the situations when fault is before the UPFC and when fault is after the UPFC. Two cases arise in case of UPFC. One is fault including UPFC in faulted section and other is UPFC is outside of faulted section. However, if the UPFC is located at the sending end of the transmission line, the UPFC will be always present in the fault loop and will affect the relay-setting characteristic. The UPFC control parameters of distance relay attributes affected by fault resistance present in case of earth fault. Measuring the crucial power frequency segments of voltage and current at relay area is utilized to ascertain the evident impedance observed by the relay 'R'. The impact of the UPFC on apparent impedance essentially relies on upon its area concerning the fault point and its working mode under the fault.

4.1 Apparent impedance calculations for UPFC

A parallel system transmission line sustained from both ends associated with UPFC, location of UPFC is changes as UPFC is associated at relay end and UPFC is associated at midpoint, in both cases are considered here. What's more, system is subjected to single line to ground fault then apparent impedance observed by relay 'R' is influenced altogether. UPFC is a mix of shunt and series devices (STATCOM and SSSC). It builds the limit of existing transmission line and controls the real and receptive power flow in the predetermined transmission lines. STATCOM and SSSC are associated with each other by a DC capacitor. Capacitor is additionally utilized as energy storage device. At the point when an UPFC is joined in a system, SSSC acquaints a variable arrangement voltage with the system. What's more, shunt device keeps up real power balance to the system. Apparent impedance can be computed for UPFC model conditions which holds good for phase a.

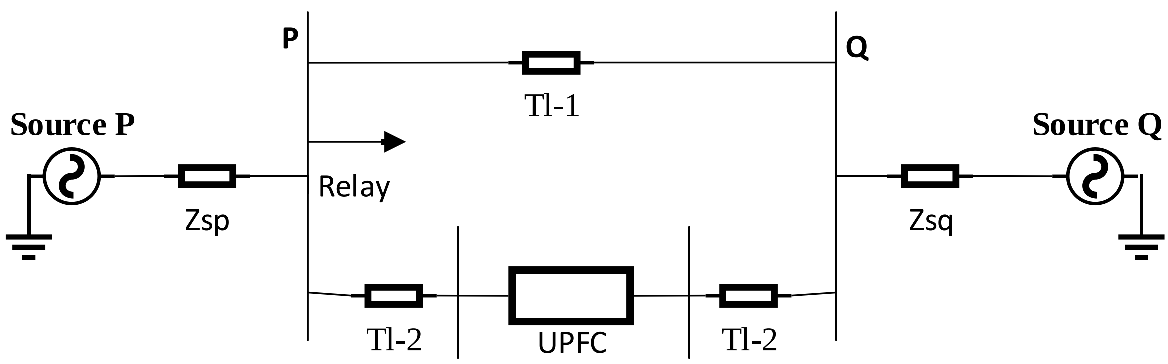

Fig 4.2 UPFC model in double circuit line

$$V_{AS1} = C_W V_{AS2} \tag{4.1}$$

$$C_W = \frac{1}{(1+r^{j\theta})} \tag{4.2}$$

$$r = \left|\frac{V_{ASE}}{V_{AS2}}\right| \tag{4.3}$$

$$I_{ASH} = \frac{(V_{AS2} - V_{ASH})}{Z_{SH}} \tag{4.4}$$

$$V_{ASH} = \frac{V_{AS1}}{C_{SH}} \tag{4.5}$$

$$V_{AS1} = he^{-j\delta} E_{AP} \tag{4.6}$$

From fig.4.2 we can write equations from 7-11.

$$I_{PS2} = I_{PS1} - I_{ASH} \tag{4.7}$$

$$I_{PS1} = I_{ASH} + I_{P2} + r^{j\theta} \frac{V_{AS1}}{Z_{1T1}} \tag{4.8}$$

$$I_P = I_{PS1} + I_{P2} \tag{4.9}$$

$$I_P = \frac{(E_{AP} - V_{AP})}{Z_{1SP}} \tag{4.10}$$

$$I_{PS2} = \frac{(V_{AS2} - V_{AF})}{Z_{1SF}} \tag{4.11}$$

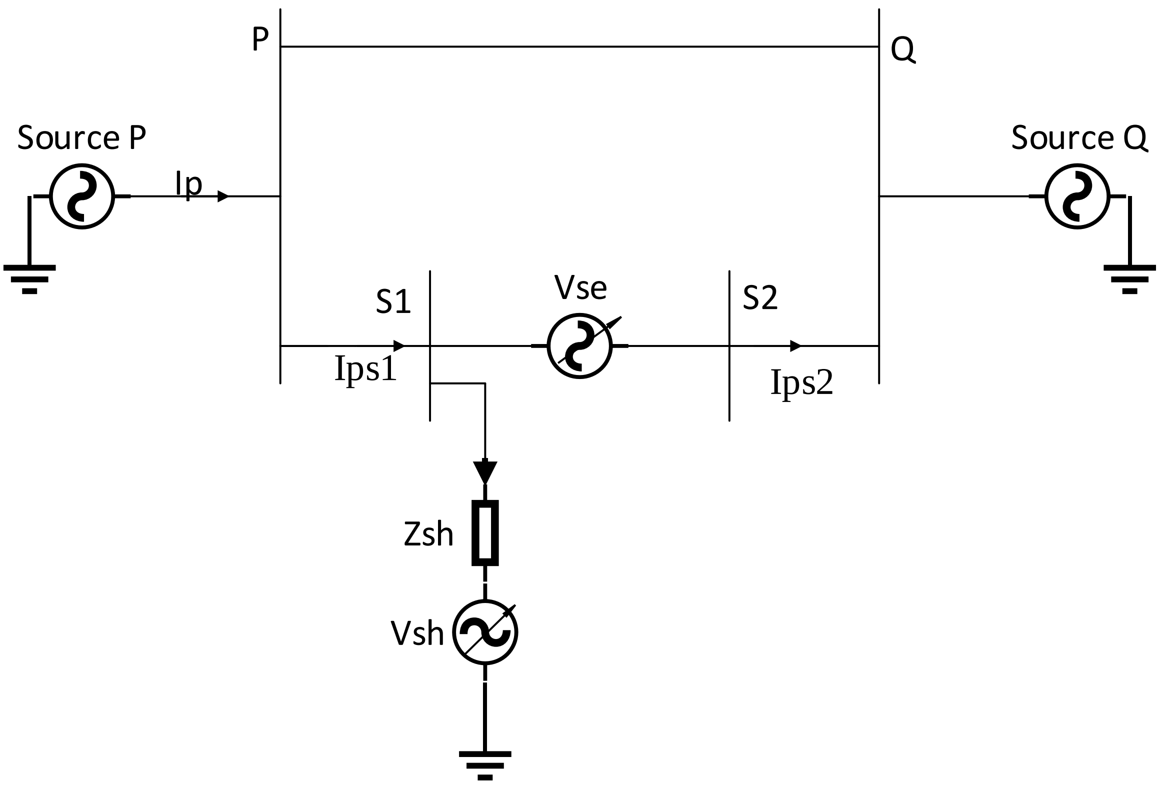

Fig 4.3 detailed model of UPFC in double circuit line

From the previous equations we get,

$$V_{AP} = C_P I_{OF} \tag{4.12}$$

$$C_P = \frac{-(3R_F + Z_\Sigma)}{\left(\left(\frac{1}{he^{-j\delta}} - 1\right)\left(\frac{Z_{1PF}}{2Z_{1SP}}\right) + \left(\frac{1}{C_W} - 1\right)\left(\frac{Z_{1PF}}{2Z_1}\right) + \left(\frac{1}{C_{SH}} - 1\right)\left(\frac{Z_{1PF}}{2Z_{SH}}\right) - \frac{1}{C_W}\right)} \tag{4.13}$$

Also we can write I_{PS2} and I_{ASH} in the equation no. (4.14) and (4.15).

$$I_{PS2} = C_{LDD} I_{OF} \tag{4.14}$$

$$I_{ASH} = C_{LSH} I_{OF} \tag{4.15}$$

Where,

$$C_{LDD} = \frac{\left(\frac{C_P}{C_W} - (3R_F + Z_\Sigma)\right)}{Z_{1PF}} \tag{4.16}$$

$$C_{LSH} = \frac{C_P\left(1 - \frac{1}{C_{SH}}\right)}{Z_{SH}} \tag{4.17}$$

Now the +ve and –ve and zero sequence impedances can be written in following equations.

$$Z_{+SQ} = Z_{-SQ}$$

$$Z_{+SQ} = \frac{n(1-n)Z_1}{2} + \frac{\left(Z_{1SP} + n\frac{Z_1}{2}\right)\left(Z_{1SQ} + \frac{(1-n)Z_1}{2}\right)}{\left(Z_{1SP} + \frac{Z_1}{2} + Z_{1SQ}\right)} \tag{4.18}$$

$$Z_{0SQ} = \frac{n(1-n)(Z_O + Z_{OM})}{2} + \frac{\left(Z_{OSP} + n\frac{(Z_O + Z_{OM})}{2}\right)\left(Z_{OSQ} + \frac{(1-n)(Z_O + Z_{OM})}{2}\right)}{\left(Z_{OSP} + \frac{(Z_O + Z_{OM})}{2} + Z_{OSQ}\right)} \tag{4.19}$$

Where, Z_{1SP}, Z_{1SQ}, are positive sequence impedances at source at 'P' and 'Q' respectively. And Z_{OSP} and Z_{OSQ} are the zero sequence impedances of sources 'P' and 'Q' respectively. Z_{OM} is zero sequence mutual impedance between transmission line TL1 and TL2 of double circuit network. n is proportional length of up to fault point from relay location.

The relay current and voltage at relay location for phase-a are obtained as following.

$$I_{AP} = I_{PS2} + I_{ASH} + I_{AS1F} + \lambda_{0T} I_{OS2F} \tag{4.20}$$

Where phase a fault current at bus S_2 is

$$I_{AS2F} = I_{1S2F} + I_{2S2F} + I_{0S2F} \tag{4.21}$$

Suffixes 0, 1 and 2 are used for zero sequence, positive sequence and negative sequence respectively. And zero sequence compensation factor is

$$k_0 = \frac{Z_0 - Z_1}{Z_1}$$

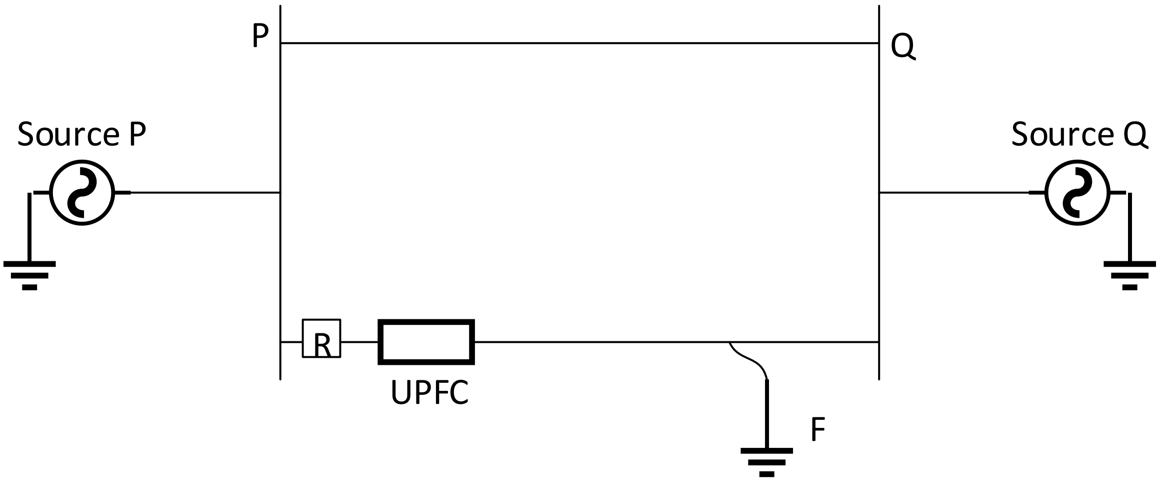

Fig 4.4 fault location w.r.t.UPFC

And the voltage at relay location can be written as following

$$V_{AP} = C_W(3R_F I_{OF} + I_{1S2F}Z_{1SF} + I_{2S2F}Z_{2SF} + I_{0S2F}Z_{0SF} + nI_{0T2}Z_{0SF} + I_{PS2}Z_{1SF}) \quad (4.22)$$

Now impedance seen by relay can be given in equation (4.23).

$$Z_{AP} = \frac{V_{AP}}{I_{AP}} = C_W(nZ_{1TL1} + \Delta Z_{CF}) \quad (4.23)$$

Where ΔZ_{CF} can be given in equation (4.24).

$$\Delta Z_{CF} = \frac{3R_F + C_m nZ_{OM} - nZ_1 C_{LSH}}{C_{LDD} + C_{LSH} + 2C_1 + C_0(1+K_0)} \quad (4.24)$$

The various terms used in equation (4.24) are given in equations (4.25-4.27).

$$C_m = \frac{n.Z_{OSQ} - (1-n).Z_{OSP}}{2.Z_{OSP} + Z_O + Z_{OM} + 2.Z_{OSQ}} \quad (4.25)$$

$$C_0 = \frac{(2-n).Z_{OSQ} + (1-n).(Z_{OSP} + Z_O + Z_{OM})}{2.Z_{OSP} + Z_O + Z_{OM} + 2.Z_{OSQ}} \quad (4.26)$$

$$C_0 = \frac{(2-n).Z_{1SQ} + (1-n).(Z_{1SP} + Z_1)}{2.Z_{OSP} + Z_O + Z_{OM} + 2.Z_{OSQ}} \quad (4.27)$$

From equation (4.23) we can easily observe that when UPFC is placed at relay location, impedance seen by the relay in case of single line to ground is dependent on the factor C_p . And it also dependent on earth fault resistance R_F, zero sequence mutual impedance, and location of fault and pre fault system conditions.

4.2 Apparent impedance calculations when UPFC is at midpoint

When UPFC is connected at midpoint then two cases arises. One is when fault occurs at F1 and does not include UPFC in fault loop. And other is SLG fault occurs at F2 and includes UPFC in fault loops. Apparent impedance seen by relay affected for both the cases.

When fault is at F2. Then apparent impedance seen by relay is given by

$$Z_A = \frac{Z_1}{2} + C_W.\left(n - \frac{1}{2}\right).Z_1 + \Delta Z \tag{4.28}$$

Where ΔZ is given by following equation

$$\Delta Z = \frac{3R_F.C_W + C_m\left(C_W.\left(n-\frac{1}{2}\right).Z_{OM} + \frac{Z_{OM}}{2}\right) - Z_1.C_{LSH}.C_W.\left(n-\frac{1}{2}\right)}{C_{LDD} + C_{LSH} + 2.C_1 + C_0.(1+K_0)} \tag{4.29}$$

Similarly for SLG fault is at F1, then apparent impedance seen by relay is given by following equation

$$Z_B = nZ_1 + \frac{3.R_F + C_m.n.Z_{OM}}{C_{LDD} + C_{LSH} + 2.C_1 + C_0.(1+K_0)} \tag{4.30}$$

Chapter 5 Effect of Wind Farm

Now a days, wind farms are most attractive form of energy. So wind farms are integrated to grid to use as base power plant. Due to uncontrollable speed of wind, its integration to the grid causes problem. However the variation in speed of wind handled by mechanical governor to a certain extent. And power electronics based control arrangement remove the problem which come from the variation in wind speed. When wind speed changes then there is change in voltage level and also change in frequency. Also due to variation in wind speed there is change in output power. Although there is nonlinear relationship between output power and wind speed. Also there is limitation in wind farms that they supply power only when the wind speed is in specified limit. Therefore the operation of distance relaying protection scheme is affected due to changes in power output of wind farm. Since a parallel transmission line have two additional effect of mutual inductance and effect of shunt capacitance. And when wind farm integrated to grid through a parallel transmission line these combined effect require a protection system which changes its characteristics according to system condition. So in this chapter Adaptive protection of transmission line connecting a wind farm is proposed.

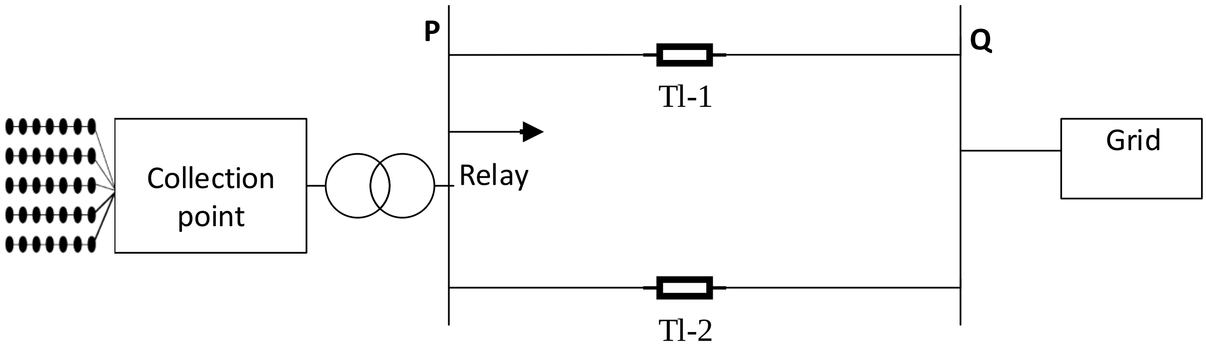

Fig 5.1 Wind Farm connected to system

It is consider that SCADA and PMU voltage and current flows are available for all section of the power system Trip boundary is set adaptively and it is assumed that SCADA and PMU voltages and line flows are available for all part of the power system. Adaptive distance relay setting for a parallel transmission line connecting a wind farm deals effectively with change in voltage change in power change in voltage angle change in source impedance and other changes of the wind farm. The ideal quadrilateral characteristics is determined for such a power system condition and the factor which affected the power system condition is pointed. When a number of wind turbine disconnected due to variation in wind speed which is not lie in specified range due to this there is change in farm side equivalent impedance and change in source impedance have significant effect on quadrilateral characteristics. Here an approach is provided for adaptive setting for protection of transmission line connecting a wind farm. By using the information of SCADA and PMU and also there is information about a number of unit participating in a wind farm. By using information of a wind farm it is simple to draw setting of distance relay. In this work we are considering a single to ground fault case the idea can be stretched to other types of faults.

$$E_{AP} = he^{-j\delta}E_{AP}$$

Where Z_{sw} is wind farm impedance.

5.1 Loading Level of wind farm

Since speed of wind is not constant and according to wind speed there is change in active power output. We know that active power is directly proportional to load angle when wind power operate at full capacity the load angle is near to 30 degree and when wind speed is low the load angle falls to a low value then in adaptive distance relay scheme we change the load angle from 30 degree to 2 degree in algorithm. And correspondingly we create the quadrilateral characteristics.

5.2 Variation in voltage level

According to wind speed there is change in reactive power output also. Since we know that reactive power is directly proportional to difference in sending and receiving end voltage since wind farm is connected to infinite bus which have a fixed magnitude of voltage and phasor. Therefore if wind speed is changed there is change in voltage of the collection centre. And according to change in voltage a quadrilateral characteristic is generated and analysed there is change in boundary when change occur in voltage at collection centre. In algorithm voltage amplitude ratio is used therefore when voltage at collection centre there is change in amplitude ratio and correspondingly there is change in setting of a relay.

5.3 Varying source impedance of wind farm

Since the rating of wind farm is low as compare to turbo and hydro generator. Also in turbo (Thermal) and hydro generator there is fixed amount of unit is operating at a time while in Wind farms the number of unit is changed according to wind condition although number of unit is also changed in case of hydro power but it does not changed in a short span of time. A number of wind turbine are taken together and then integrated to the grid. Due to low and high speed of wind, the number of wind turbine functioning at a time will changes due to failure of unit connected to grid bus at a time. Therefore the impedance of wind farm changes corresponding to number of unit operated at that time

If we use a conventional distance relay it read as a fault for change in source impedance but actually it is not so a conventional relay whose setting is fixed will malfunction in this condition. Therefore an Adaptive approach is required which consider the effect of change in source impedance.

Chapter 6 Results and Discussions

6.1 Generation of tripping boundary

When mutual impedance and shunt coefficient are taken into consideration, for single line to ground fault tripping boundary is generated.

6.1.1 Case A for Upper Boundary

Faults at a relay-reach end (80% of line) with different fault resistance up to 200 Ω. So for fault at 80% of line, taking p=0.8 (constant) and RF varies from 1ohm to 200 ohm in a step of 20 ohm. Then upper side tripping boundary is generated.

Table 1. Values of R and X for upper side boundary

Fault Resistance (in Ω)	**Fault position (as percentage of line length)**	**Impedance seen by Relay Z_{post}**	
		R_{post}	X_{post}
1	80	5.2	30
21	80	35.9	45
41	80	82.63	55
61	80	128	60
81	80	172	63
101	80	214	65
121	80	254	67
141	80	293	68
161	80	331	69
181	80	368	70
200	80	403	71

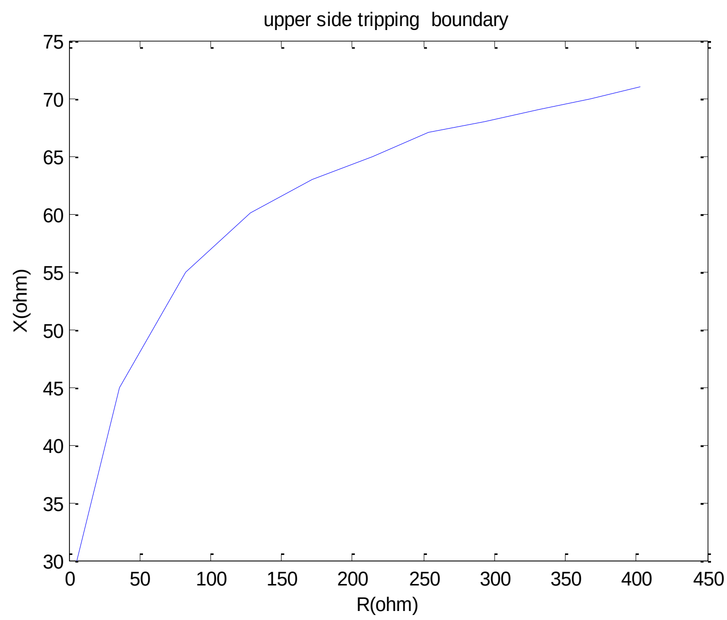

Fig 6.1 Upper side boundary

6.1.2 Case B for right side Boundary limit

Faults at different points with a 200 Ω fault resistance. In this case fault resistance is constant at 200 ohm, and fault location from relay point is varied by varying the value of p from 0.01 to 0.8 (80% of the line). Then right side tripping boundary is generated.

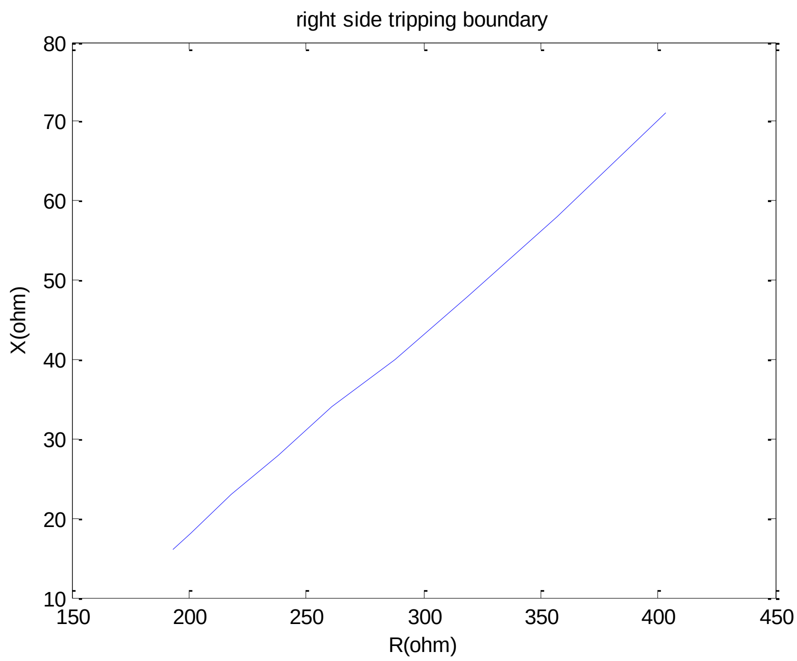

Fig 6.2 right side tripping boundary

Table 6.2 Values of R and X for right side boundary

Fault Resistance (in Ω)	**Fault position (as percentage of line length)**	**Impedance seen by Relay Z_{post}**	
		R_{post} (in Ω)	**X_{post} (in Ω)**
200	1	193	16
200	11	20135.9	18
200	21	21882.63	23
200	31	238 128	28
200	41	261172	34
200	51	288 214	40
200	61	319254	48
200	71	357 293	58
200	80	403 331	71

6.1.3 Case C for bottom side boundary

Faults at the relaying point with different fault resistance up to 200 Ω . It means p=0.01 is constant in this case and fault resistance RF is varied from 1 ohm to 200 ohm in a step of 20 ohm. Then bottom side tripping boundary is generated.

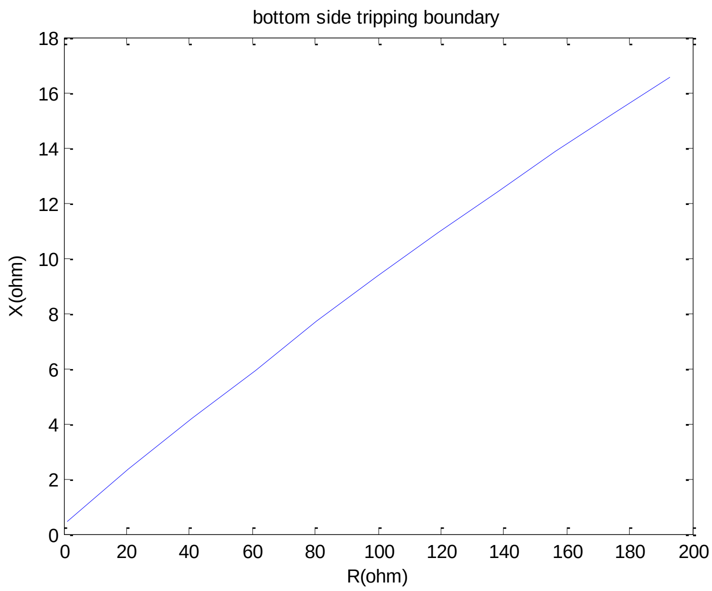

Fig 6.3 Bottom side boundary

Table 6.3 Values of R and X for bottom boundary

Fault Resistance (in Ω)	Fault position (as percentage of line length)	Impedance seen by Relay Z_{post}	
		R_{post} (in Ω)	X_{post} (in Ω)
1	1	1.00	0.47
21	1	20.60	2.34
41	1	40.88	4.20
61	1	60.87	5.90
81	1	80.60	7.70
101	1	99.99	9.34
121	1	119.14	10.91
141	1	138.00	12.42
161	1	156.60	13.86
181	1	174.90	15.24
200	1	193.00	16.00

6.1.4 Case D for left side boundary

Faults at different locations in line with RF=1 ohm constant. And varying the value of p from 0.01 to 0.8 (80% of the line). Then right side tripping boundary is generated. Then left side boundary is generated.

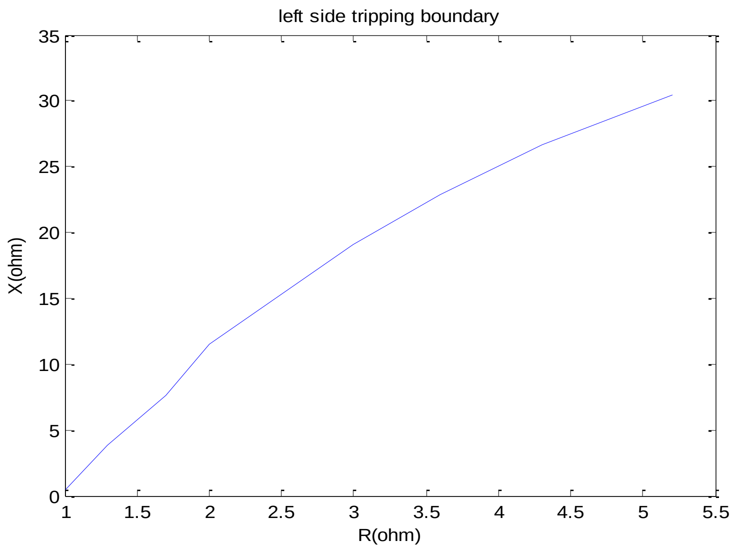

Fig 6.4 left side tripping boundary

Table 6.4 Values of R and X for left side boundary

Fault Resistance (in Ω)	**Fault position (as percentage of line length)**	**Impedance seen by Relay Z_{post}**	
		R_{post} (in Ω)	**X_{post} (in Ω)**
1	1	1.00	0.47
1	11	1.30	3.80
1	21	1.70	7.60
1	31	2.00	11.48
1	41	2.50	15.29
1	51	3.00	19.11
1	61	3.60	22.91
1	71	4.30	26.71
1	80	5.20	30.00

6.2 Final trip characteristics

6.2.1 Final plot for considering mutual impedance

Quadrilateral relay characteristics can be obtained by combining all four plots in a single graph.

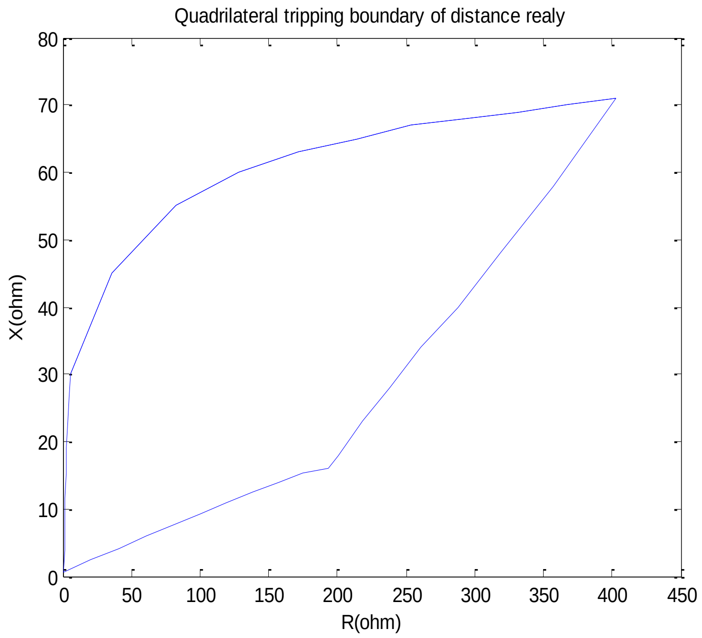

Fig 6.5 final characteristic of quadrilateral relay

6.2.2 Comparison in only mutual impedance and mutual impedance with shunt coefficient

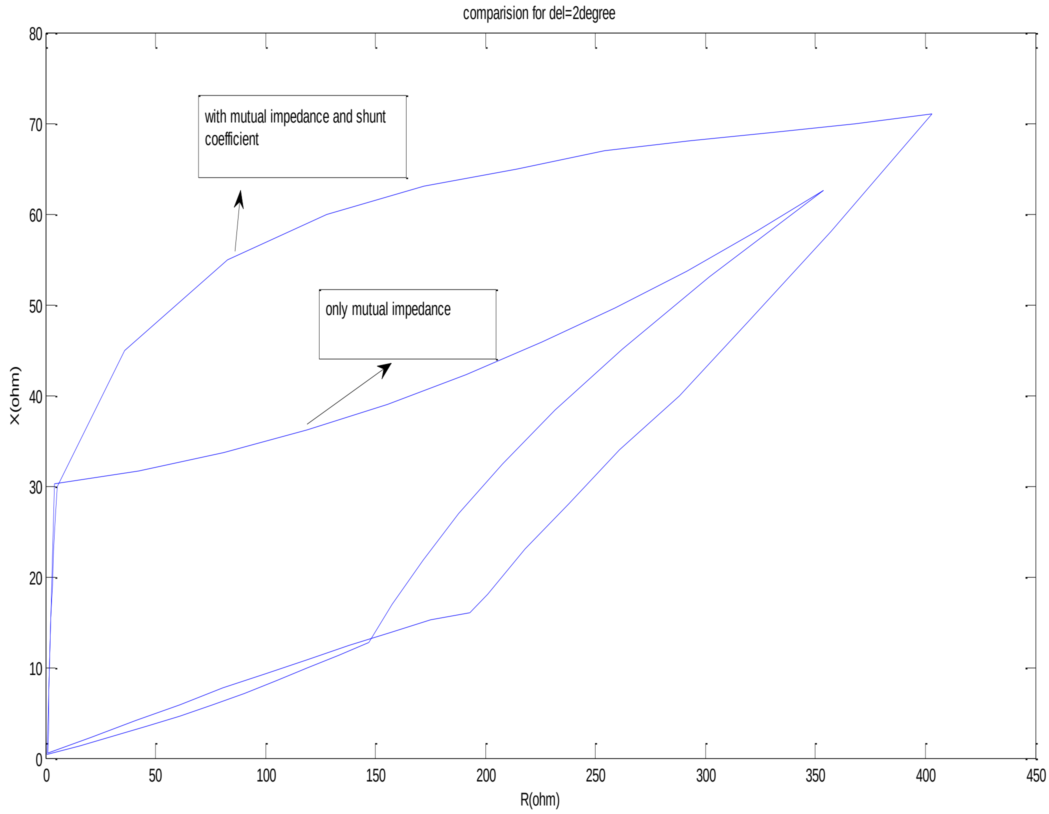

Fig 6.6 comparisons of characteristics

6.3 Effect of UPFC

6.3.1 When UPFC is at relaying point

For different conditions are considered here. UPFC parameters varied and its effect on apparent impedance seen by the relay is shown in tables. Unified power flow controller parameters r, θ can be varied, r is varied from 0.0 to 0.5 while θ is varied 0^o to 360^o. The shunt voltage source of UPFC converter is represented by a voltage source V_{sh} and Z_{sh}. Following power balance equation is used to obtain the value of V_{sh}.

$$Re(V_{AS1} I_{ASH}{}^*) = Re\left(rV_{AS1} e^{j\theta} I_P{}^*\right)$$

Assuming the SLG fault at point F in figure 1 at a distance of 0.95 of the total length of transmission line. Table 1 shows the apparent resistance and reactance seen by the relay, when Unified power flow controller is connected at relay location. The real and imaginary parts of the impedance shown for different values of r from 0.0 to 0.5 in a step of 0.1. And discrete values of θ at an angle of $0^o, 90^o$ and 270^o.

And when UPFC is connected at midpoint then for SLG fault, the real and imaginary parts of impedance seen by relay is shown in tables for different values of r and θ.

From the above results it can be easily observed that when UPFC is located at relay point and $\theta = 0^{\circ}$ and r increased from 0 to 0.5. then resistance and reactance seen by the relay decreases(table 5.)

Table 6.5 UPFC at relay point R_F=5Ω and$\theta = 0^o$

r	R	X
0.0	24.0117	32.4129
0.1	22.5331	31.8617
0.2	20.9856	31.1194
0.3	19.4833	30.2524
0.4	18.0785	29.3153
0.5	16.7910	28.3485

.

And at $\theta = 90^{\circ}$, resistance increases and reactance decreases as r increases from 0 to 0.5(table 6.)

Table 6.6 UPFC at relay point R_F=5Ω and $\theta = 90^o$

r	R	X
0.0	24.0117	32.4129
0.1	24.5856	31.1125
0.2	25.4029	29.8176
0.3	26.3441	28.3711
0.4	27.2642	26.7205
0.5	28.0440	24.8910

And at $\theta = 270^{\circ}$ resistance decreases and whereas reactance increases as r increases from 0 to 0.5(table 7.)

Table 6.7 UPFC at relay point R_F=5Ω and $\theta = 270^o$

r	R	X
0.0	24.0117	32.4129
0.1	23.7005	33.9733
0.2	23.4942	36.0811
0.3	23.0264	38.9311
0.4	21.7891	42.4727
0.5	19.3198	46.3183

6.3.2 UPFC at midpoint

When UPFC is located at midpoint results from above can be seen easily. At $\theta = 0^{\circ}$ and r increased from 0 to 0.5. then resistance seen by the relay decreases whereas reactance shows also increases (table 8). And at $\theta = 90^{\circ}$, resistance decreases and reactance also decreases but shows less change as r increases from 0 to 0.5 (table 9.). At at $\theta = 270^{\circ}$, resistance increases and reactance also increases as r increases from 0 to 0.5 (table 10.)

Table 6.8 UPFC at midpoint R_F=5Ω and $\theta = 0^o$

r	R	X
0.0	24.9982	33.0317
0.1	23.6100	35.0777
0.2	22.1344	36.4964
0.3	20.6915	37.4548
0.4	19.3377	38.0798
0.5	18.0950	38.4649

.

Table 6.9 UPFC at midpoint R_F=5Ω and $\theta = 90^o$

r	R	X
0.0	24.9982	33.0317
0.1	22.7554	32.1165
0.2	20.9435	31.7327
0.3	19.5695	31.6278
0.4	18.5659	31.6241
0.5	17.8391	31.6170

.

Table 6.10 UPFC at midpoint R_F=5Ω and $\theta = 270^o$

r	R	X
0.0	24.9982	33.0317
0.1	27.5319	34.7759
0.2	30.0333	37.6184
0.3	31.9907	41.6787
0.4	32.7903	46.7882
0.5	31.9147	52.4173

These results shown by the tables clearly depicts that presence of UPFC alters the impedance seen by the relay as it introduces inductive and capacitive effects to the transmission line which varies as the UPFC parameters such as r, θ , location of UPFC and fault location etc.

6.4 Generation of Relay Trip characteristics including UPFC

6.4.1 UPFC at relaying point

1. for r = 0.5 and θ =90 degree and UPFC is placed at relaying point and fault occurs at one of the transmission line then following relay characteristic is obtained.

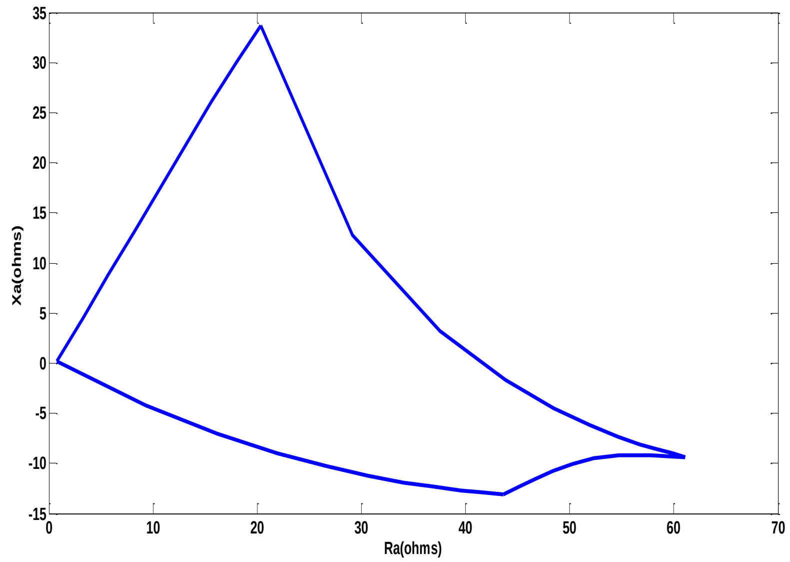

Fig 6.7 tripping characteristics for r=0.5 and θ =90

2. for r =0.5 and θ=270 degree and UPFC is placed at relaying point and fault occurs at one of the transmission line then following relay characteristic is obtained.

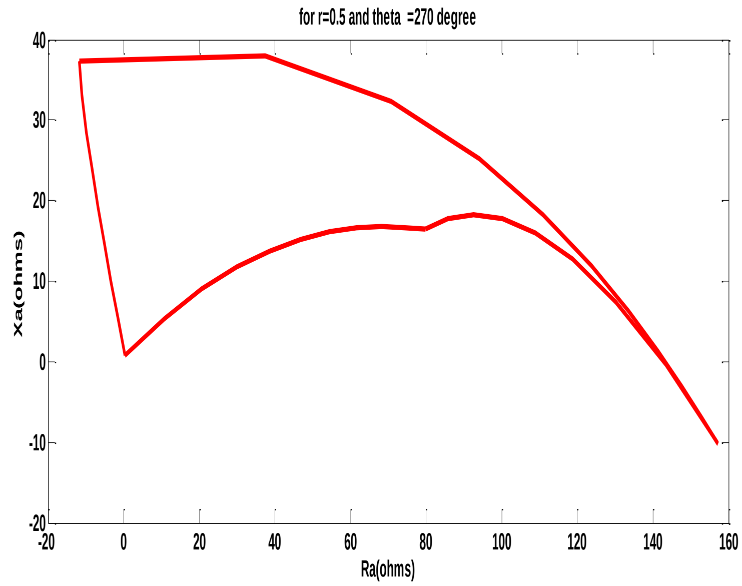

Fig 6.8 tripping characteristics for r=0.5 and θ =270 degree

3. for r =0.5 and θ =0 degree and UPFC is placed at relaying point and fault occurs at one of the transmission line then following relay characteristic is obtained.

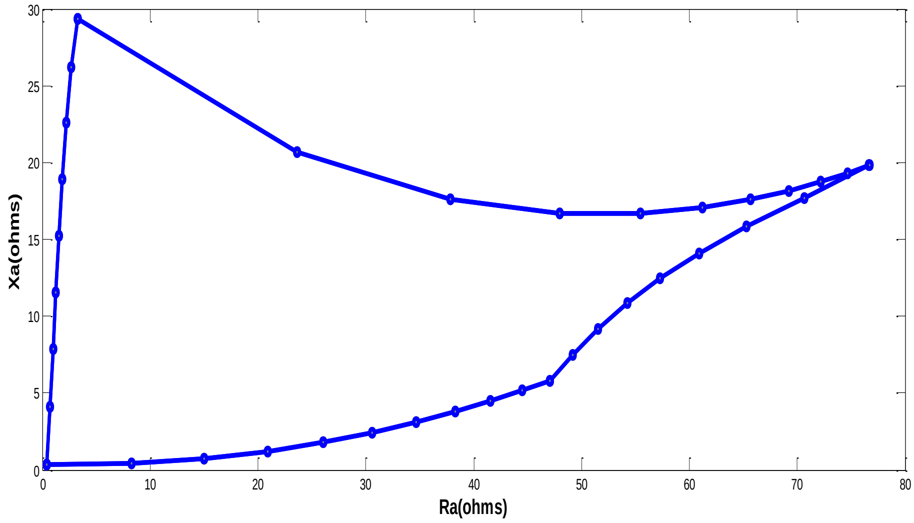

Fig 6.9 Tripping characteristics for r=0.5 and θ =0 degree

6.4.2 Trip characteristics when UPFC at midpoint

1. for r = 0.5 and θ =90 degree and UPFC is placed at midpoint and fault occurs at one of the transmission line then following relay characteristic is obtained. So here we can easily observe that two boundaries are obtained for relay characteristics.

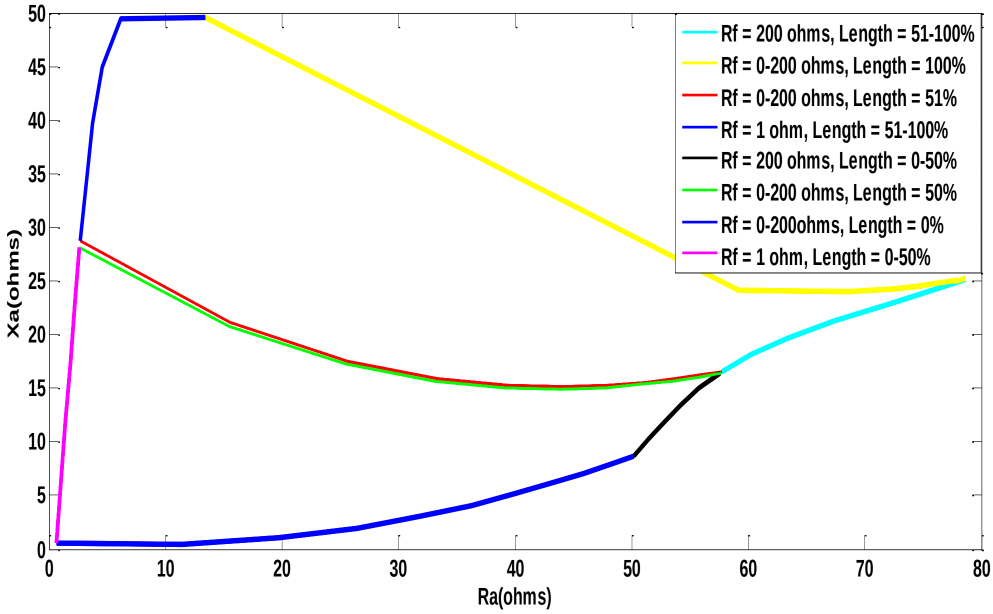

Fig 6.10 Tripping characteristics for r=0.5 and θ =90

2. for r = 0.5 and θ =270 degree and UPFC is placed at midpoint and fault occurs at one of the transmission line then following relay characteristic is obtained. So here we can easily observe that two boundaries are obtained for relay characteristics.

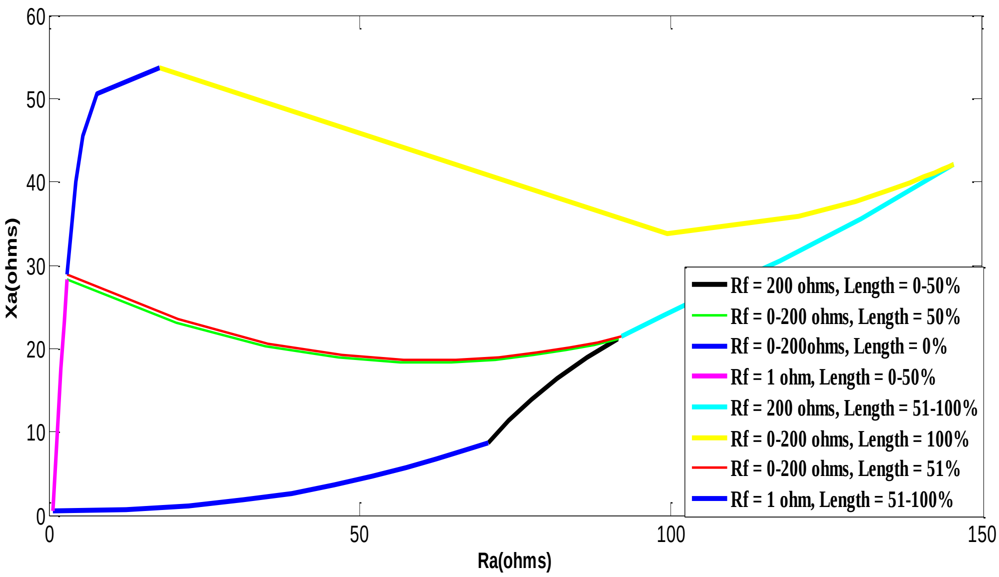

Fig 6.11 Tripping characteristics for r=0.5 and θ =270

3. for r = 0.5 and θ =0 degree and UPFC is placed at midpoint and fault occurs at one of the transmission line then following relay characteristic is obtained. So here we can easily observe that two boundaries are obtained for relay characteristics.

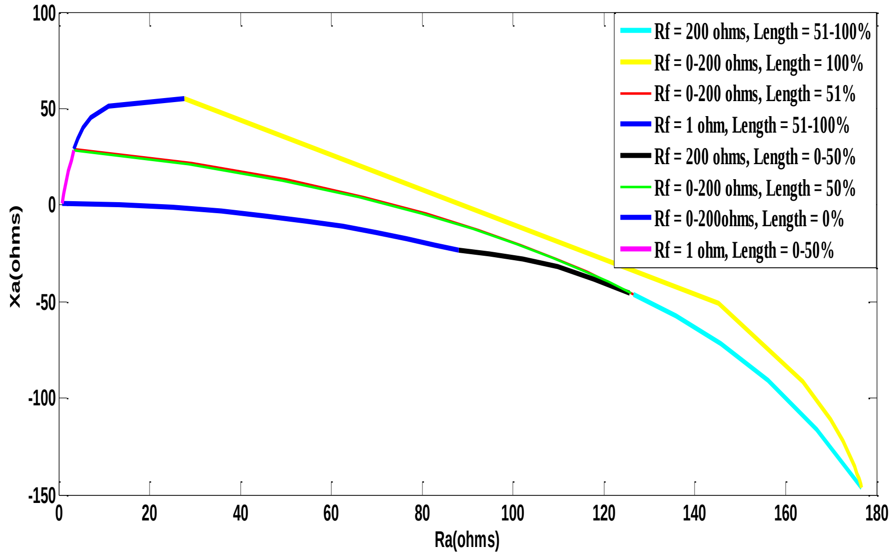

Fig 6.12 Tripping characteristics for r=0.5 and θ =0

6.5 Effect of Wind Farm when UPFC effect not included

1. Variation in delta from 30 degree to 2 degree. Here wind farms alone is considered along with parallel system network. So wind fluctuates

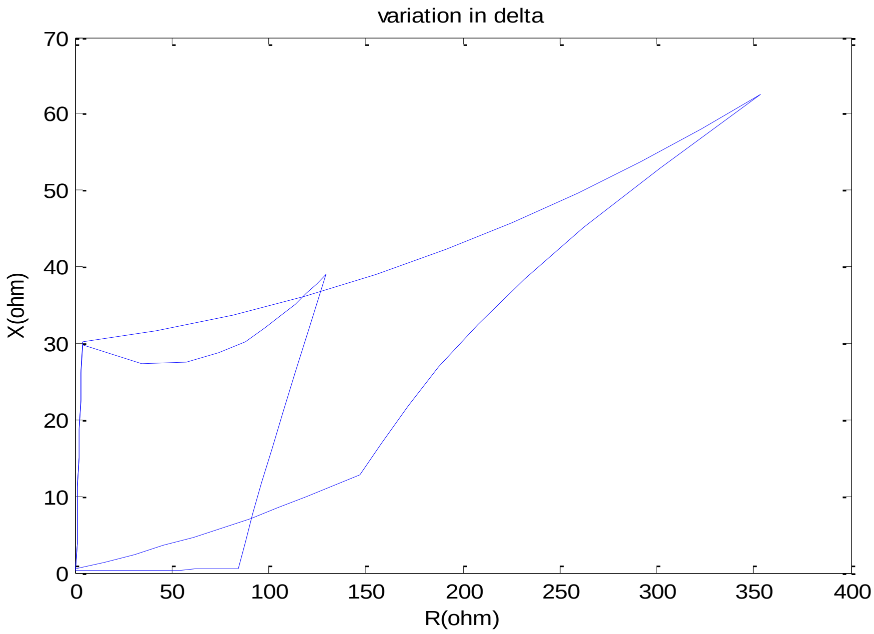

Fig 6.13 variation in delta

2. Variation in voltage amplitude ratio for h=0.98 and 1.0

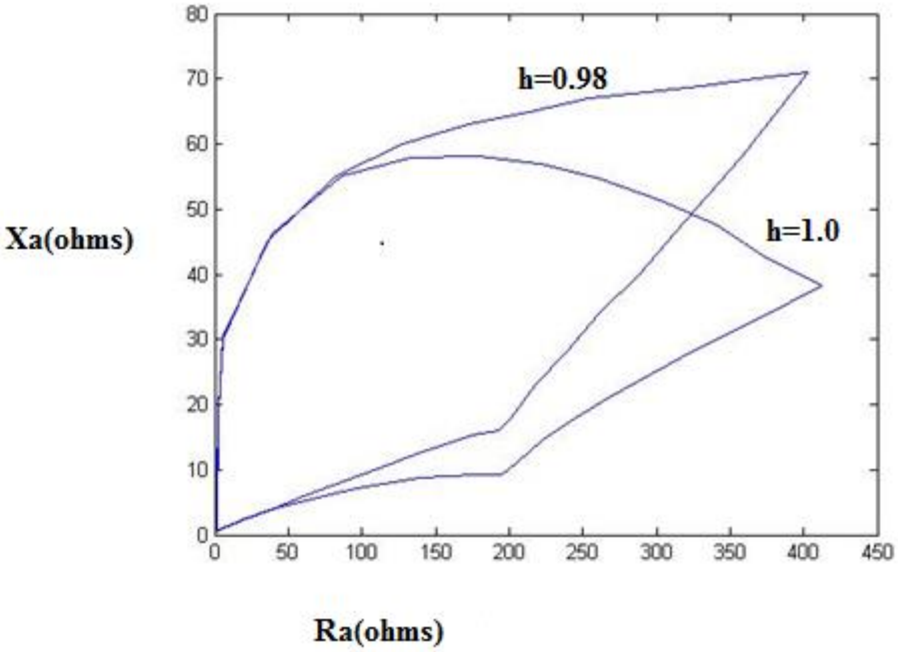

Fig 6.14 variation in h

6.6 Effect of UPFC and Wind Farm both

There are two cases arises again. One is UPFC is available at relaying point and other is UPFC is connected at midpoint. And we can observe the difference in the tripping characteristics of relay in both the cases. And the effect of wind farm is introduced then observing the tripping characteristics.

6.6.1 UPFC at relaying point

1. Variation in delta, when UPFC is located at relaying point as we know wind speed is variable and it affects the power transfer angle delta, here taking two extreme cases delta for 20 degree for normal case, and when delta is severely affected taking 2 degree. Boundary of relay trip characteristics changes and increases its tripping area when power transfer angle decreases drastically.

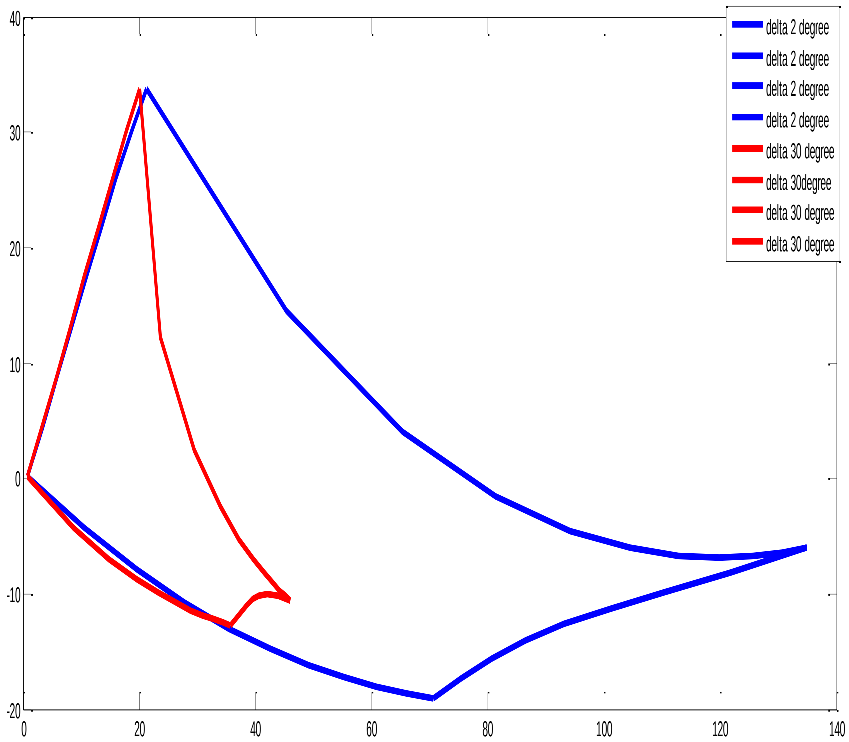

Fig 6.15 variation in delta when UPFC at relaying point

2. Variation in voltage amplitude ratio, when UPFC is located at relay point. As we know wind speed also affects the voltage magnitude of the bus connected to wind farms. So by varying the h, we can see the its effect on the relay tripping characteristics. It is shown in fig 6.16.

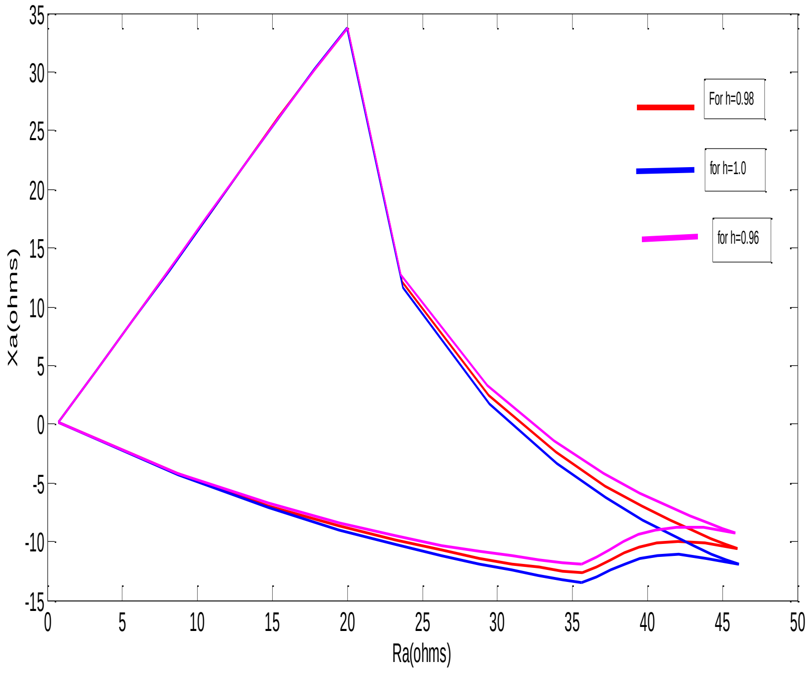

Fig 6.16 variation in voltage ratio when UPFC is at relaying point

6.6.2 UPFC at midpoint

1. Variation in delta when UPFC is located at midpoint. Delta is taken 20 degree and for 2 degree. Then relay trip characteristics modifies and shows negative values of resistance and it is shown in fig 6.17.

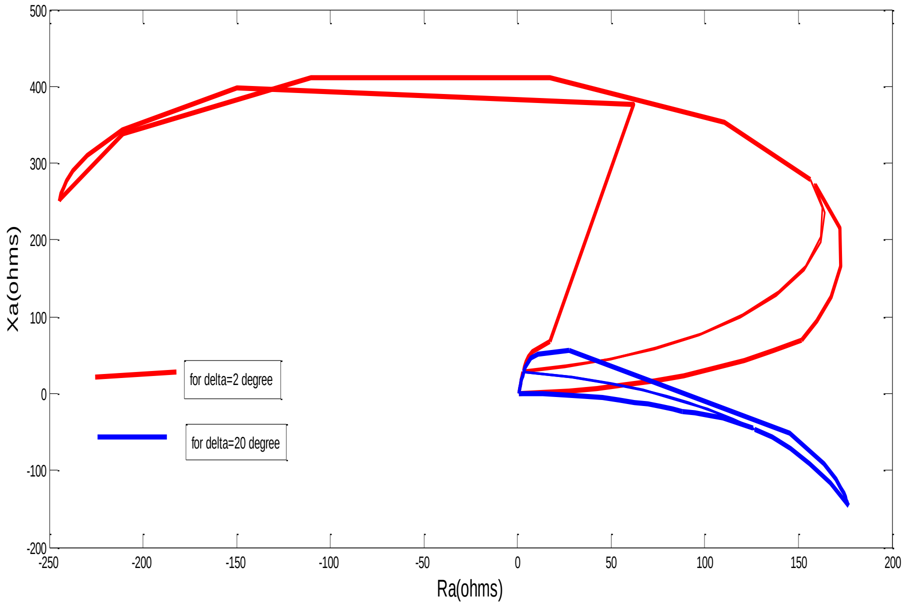

Fig 6.17 variation in delta when UPFC at midpoint

2. UPFC is located at midpoint and wind effect taken into consideration for voltage amplitude ratio of two sources. As h varies impedance seen by relay affected so the relay characteristics must be changed according to system parameter.

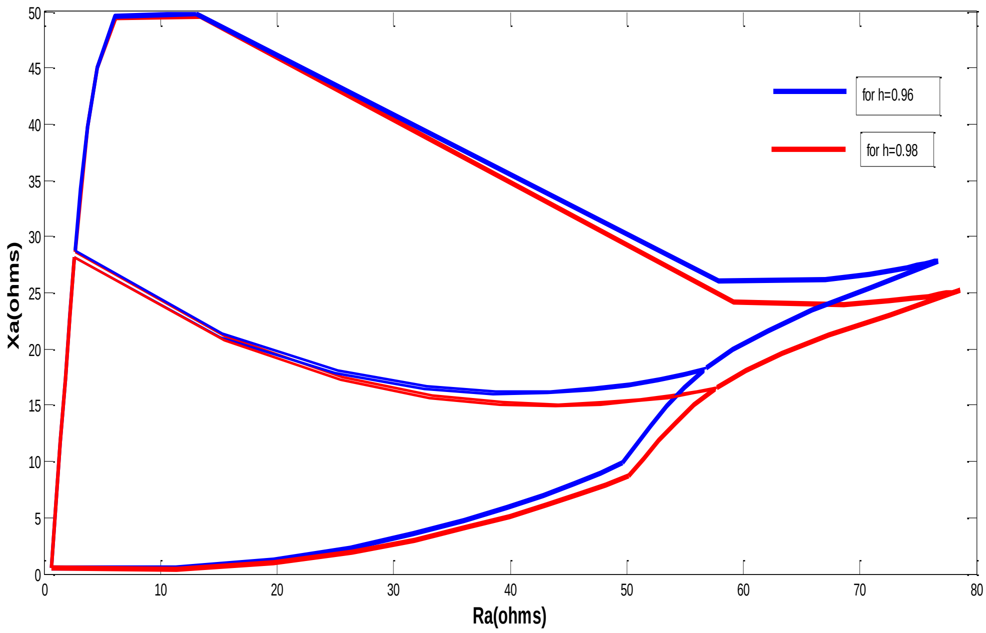

Fig 6.18 variation in voltage amplitude ratio when UPFC at mid point

Conclusion and Future scope

From the above theory and result shown now it can be summarised that when wind farm and UPFC are connected in parallel transmission network apparent impedance seen by the relay is affected. For protection of such a parallel network adaptive distance relay is required which changes tripping characteristics according to online system conditions changes.

The proposed study can be reach out for applying similar strategies to the high voltage transmission line connected various FACTS devices which are not considered in the present thesis. Dynamic model of UPFC and Dynamic model of Wind farm may also be considered for future study. And for enhancing the protection system of transmission system connected dynamic devices requires proper coordination of relays. It can be done with the help of remote sensing devices. So by using remote sensing devices , Adaptive relay setting for distance relay might be considered the potential area for future study.

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